J. EDUCATIONAL COMPUTING RESEARCH, Vol. 29(3) 315-324, 2003

VISUOSPATIAL COGNITION IN ELECTRONIC LEARNING

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ABSTRACT

Static, animated, and interactive visualizations are frequently used in electronic learning environments. In this article, we provide a brief review of research on visuospatial cognition relevant to designing e-learning tools that use these displays. In the first section, we discuss the possible cognitive benefits of visualizations consider used in e-learning environments. In the second section consider cognitive constraints on the use of visualizations and design guidelines intended to reduce impact of these cognitive constraints. Finally, we consider how individual differences interact with learning from visualizations and how the use of visualizations might be altered for students of different abilities.

One of the major potential benefits of electronic learning environments is the relative ease of representing information in visual rather than simply textual form. Visually-presented information in electronic media may include static inscriptions that are also available in print media such as graphs, diagrams, maps, and pictures (Winn, 1987). Such displays are quite common in textbooks (Mayer, 1993). However, e-learning can also incorporate visual displays that are animated or interactive. Even when static diagrams are presented in electronic media, their use is potentially altered compared to their use in text-based media. In electronic media, for example, color has no added cost (unlike in print) and can be used extensively. In addition, electronically-presented visualizations may be moved, re-sized, or made to disappear.

The *a priori* assumption is that visualizations used in e-learning environments benefit learning. Thus, it is not surprising that graphs, diagrams, illustration, animations, and video are frequently used in electronic learning environments, especially in the context of mathematics and science. Although providing instructional materials in a visuospatial format in a computer-based or Web-based environment has considerable intuitive appeal, the ability to demonstrate empirically that visual information in a computer-based medium promotes learning remains a daunting task (van Bruggen, Kirschner, & Jochems, 2002). Many common sense views about multimedia learning are not supported by the empirical literature (Mayer, in press). For example, it appears intuitive that animation might help viewers comprehend change over time. However, a positive benefit of animation is difficult to identify in well-controlled studies comparing static diagrams that contain equivalent information as animated ones, as suggested by a recent review of the animation literature (Tversky, Morrison, & Betrancourt, 2002).

When are technological advances for presenting visual information beneficial and when are they either not helpful or even harmful? Research on the cognitive processes and representations involved in remembering, manipulating, and interpreting visual or spatially coded information is a flourishing subfield in cognitive psychology which we will argue in this article has implications for the comprehension and use of static, animated, and interactive visualizations in e-learning environments. We divide this article into three sections. In the first section, we discuss the possible cognitive benefits of visualizations used in e-learning. In the second section, we consider cognitive constraints on the use of visualizations and provide guidelines to overcome these constraints. And in the third section, we consider how individual differences in learning style (e.g., visual vs. verbal) and cognitive abilities (and, in particular, visuospatial abilities) might interact with learning from visualizations.

We note that this is a selective review due to the length requirements. Thus, we point readers to important review articles and books as well as classic theoretical and experimental pieces so that readers can read more about the topics discussed.

POTENTIAL BENEFITS FOR VISUALIZATIONS IN E-LEARNING

Paivio's dual-coding theory (Clark & Paivio, 1991) has frequently been used to justify the cognitive benefits of presenting information both visually and verbally in instructional contexts (Mayer, 2001). According to dual-coding theory, the superiority of presenting information in visual and verbal form over merely verbal form is that information is encoded in two modalities rather than a single modality. Thus, students have multiple retrieval cues that facilitate the retrieval of information from memory. Much research demonstrates that presenting instructional

materials in both a textual and visual format does in fact promote learning (Mayer, 2001). However, other factors may also be responsible for the benefit of using visualizations.

One additional benefit of visualizations is that they provide an external representation of information that has analog properties (Hegarty & Steinhoff, 1997; Zhang, 1997). Because information is depicted in the environment, students do not have to maintain a mental representation of that information or mentally transform it. Consequently, such displays may reduce the cognitive load required to comprehend the information presented.

A second additional benefit of visualizations, and in particular interactive visualizations, is that they may produce deeper processing because they allow users to select, compare, and integrate materials with other available materials as well as their own prior knowledge (Mayer, 2002, in press). Wiley and Voss (1999) found that presenting text and other visual information in Web-form so that relevant information could be placed next to each other led to students writing more integrated and causal essays than presenting information in traditional textbook format. Similarly, Rieber (1990) found that animated displays that required active interactions facilitated science learning.

A third additional benefit of visualizations is that they can be attractive and motivating. Viewers' attention is drawn to these displays, and students will be more apt to study them for longer periods of time (Shah, in press). VanderStoep, Fagerlin, and Feenstra (2000) found that students in introductory psychology courses attended to and recalled materials presented in videos better than information presented in the text alone. Similarly, Rieber (1990) found that students who engaged in an interactive animation lesson on Newtonian physics were more likely to select returning to the animation following the post test than other activities (e.g., puzzles). However, it is not clear what the attentional or motivational impact of visualizations might be. In some studies, animations and other visualizations are not always preferred, and some people even choose not to use them (e.g., Pane, Corbett, & John, 1996).

Finally, and perhaps most importantly, visualizations can make complex information easier to comprehend (Larkin & Simon, 1987; Oestermeier & Hesse, 2000; Zhang & Norman, 1994). Visual displays are particularly beneficial to the comprehension of some classes of concepts. Specifically, visual displays are useful for communicating cause-and-effect information such as how turning a key can unlock a door (Mayer, 2001; Oestermeier & Hesse, 2000). When such displays highlight the cause-and-effect sequence (e.g., by animating one portion at a time, or by using a sequence of arrows), viewers' comprehension and memory for the cause-and-effect information is enhanced (Mayer, 2001). Second, visual displays are frequently useful for representing relationships amongst elements that are difficult to explain verbally (e.g., a Venn diagram, a text-based graphic organizer, a scientific model; e.g., Robinson & Skinner, 1996). One benefit of such representations is that they can facilitate problem-solving (Oestermeier &

Hesse, 2000). Finally, computer-based visualizations may also be particularly useful when dealing with sequential or temporal relations. Animations or videos can guide a viewers' attention from one step to the next. Or, a sequence of panels might instruct someone how to bake cookies (Michas & Berry, 2001). Such displays, by highlighting information or key elements in a sequence, help students learn and remember the relevant information.

Animations seem intuitively like an ideal format for representing change over time and many studies show a benefit for animations (e.g., Park & Gittelman, 1992). However, when static displays, such as the sequence of panels used in Michas and Berry (2001), contain approximately equivalent information as animations then animations show no additional benefit (see also Hegarty, Quilici, Narayanan, Holmquist, & Moreno, 1999; Tversky et al., 2002). Unfortunately, many studies that compare animation to static formats use static diagrams that do not depict all the microsteps necessary to deeply understand the material. In other studies, participants are able to interact with animations but not with static (Tversky et al., 2002). Thus, if static diagrams are well-designed and allow users to appropriately interact with the information presented, animation does not appear to be beneficial. However, given current technology and the difficulty of designing appropriate static controls, it might actually be easier to create an animation that by definition contains all the changes than to design static diagrams. Thus, animations may in practice be better for presenting change over time.

COGNITIVE CONSTRAINTS ON USING VISUALIZATIONS IN E-LEARNING

Although visualizations can be beneficial, one potential constraint is that complex visualizations can be cognitively demanding. Specifically, using visualizations typically requires integrating or coordinating auditory or textually presented information with visual information (e.g., van Bruggen et al., 2002). In addition, viewers may be required to form a mental model or mentally animate visually-presented information (Hegarty & Just, 1993). Such tasks require actively maintaining and mentally manipulating visual and verbal information. The cognitive system that supports this maintenance and processing, *working memory*, is highly limited in the amount of information that can be actively maintained at any time. This limit is greatest when to-be-maintained information is novel, which is frequently the case when viewing instructional visualizations (Miyake & Shah, 1999). In addition to working memory, the comprehension of visualizations is constrained by the perceptual modalities in which information is presented. It is impossible to read a text and look at a diagram simultaneously but it is possible to view a diagram while listening to a text, for example.

Much research has demonstrated the limitations that might constrain the interpretation of visualizations and led to guidelines that reduce the impact of these

limitations (Mayer, 2001; Narayanan & Hegarty, 1998; Sweller, van Merrienboer, & Paas, 1998). One factor that influences cognitive load is the amount of information presented. Mayer, Heiser, and Lonn (2001) found that students who received a basic presentation about lightening (i.e., lacking additional words, sounds, or video) demonstrated superior problem-solving transfer than did students who received an expanded version (i.e., with music, sound effects, and/or video). In a related study, Mayer et al. (2001) showed that when students viewed a lightening bolt hitting a person on the ground in a lesson about how lightening works, they understood the scientific principles discussed less than when the text did not contain such "seductive details." These studies suggest that cognitive load may be reduced by not having multiple pieces of information competing for limited resources, especially when some of the information is less relevant for learning. In other words, in some cases, "less is more."

A second factor that influences cognitive load is the relative difficulty of integrating multiple pieces of information. People are better able to integrate information that is within close physical proximity. Sweller et al. (1998) found a benefit for presenting statements of relevant theorems used in a geometry proof right next to relevant portions of a diagram rather than on a different part of a screen or page. Presenting some information in auditory form while visual information is presented on a screen so that viewers do not have to look in more than one place to integrate is also beneficial (Mayer, 2001). Thus, by presenting to-be-integrated information close together or in separate modalities supports comprehension of visualizations.

A third factor that influences the cognitive demands of a display is the extent to which information must be mentally transformed (Larkin & Simon, 1987). For example, when maps are presented in a manner that requires mentally aligning or rotating information in order to understand it or use it for navigation, comprehension is difficult (Wickens, Vincow, & Yeh, in press). Similarly, Shah, Mayer, and Hegarty (1999) found that students' graph comprehension was facilitated when graphs were designed to reduce cognitively demanding transformations, such as converting information from absolute values to percentage values, were needed to understand the relevant information. In general, information should be presented in a manner requiring minimal cognitive computation for comprehension of the most important information in a visualization.

Finally, one factor that appears to both increase and decrease cognitive load is the degree to which illustrations are realistic or schematic. In many cases, greater realism comes with cognitive costs, in that, viewers may reduce their situational understanding of the environment (Wickens et al., in press). At the same time, realism can help viewers form mental models of visuospatial information that are not available in schematic diagrams. Schwartz and Black (1996) found that realistic pictures of hinges and gears helped viewers mentally animate the working of these mechanical systems compared to schematic drawings. One solution proposed by Narayanan and Hegarty

(1998) is to provide both schematic and realistic diagrams depending on the learners' goals.

INDIVIDUAL DIFFERENCES ON THE USE OF VISUALIZATIONS IN E-LEARNING

Research on visuospatial cognition has demonstrated that learning style (visual vs. verbal) influences the degree to which visualizations are effective for learners. Some individuals use visual-spatial representations while solving problems that can be solved by either visual-spatial or more abstract analytical methods (Hegarty & Kozhevnikov, 1999; Kozhevnikov, Hegarty & Mayer, in press); these students may be more likely to benefit from visualizations.

Individuals also differ in their visuospatial abilities. Typically, visualizations benefit those learners who have high spatial abilities more than those who have low visuospatial abilities (e.g., Gyselinck, Cornoldi, Dubois, De Beni, & Ehrlich, 2002). One reason for this, discussed above, is that many visualizations are highly demanding of cognitive resources, such as working memory and in particular spatial working memory (e.g., Hegarty & Steinhoff, 1997). It is possible, however, that well-designed visualizations may actually help low visuospatial ability learners understand inherently visuospatial information that is difficult for them to understand precisely because they are unable to mentally animate or integrate information. In one promising study, Vekiri (2001) recently found that low spatial ability students were helped by presentation of weather maps in integrated format but high spatial ability students were less benefited.

The main conclusion from this research is that designing displays that benefit low visuospatial ability learners rather than hinder them from comprehending the material is important. This is especially true considering the importance of visualizations in mathematics and science education and the substantive sex differences that have been found in visuospatial abilities (see Halpern & Collaer, in press). A further benefit of designing visualizations for low ability users is that using and interacting with them may, in turn, have a positive impact on their visuopatial abilities. One study supporting this possibility found that playing video games (which involves interacting with complex visualizations) has a positive impact on spatial abilities (Subrahmanyam & Greenfield, 1994).

In addition to individual differences in spatial abilities, developmental differences also have an influence on viewers' ability to learn from visualizations (Blades & Spencer, 1989; Somerville & Bryant, 1985). As Shah (Shah & Hoeffner, 2002; Shah, Freedman, & Vekiri, in press) reviews, for example, young students are more likely to misinterpret visual representations of abstract concepts as an iconic representation of a real event. For example, children might interpret a graph of the height of a river at different times of year to be a map or picture of the river. Young students also have difficulty maintaining and transforming visuospatial information, coordinating visuospatial information, and

so on (e.g., Blades & Spencer, 1989; Somerville & Bryant). Thus, complex visualizations must be tied to the students' level of visuospatial development.

Prior knowledge also has an impact on the comprehension of visualizations. In our own studies of the comprehension of graphs, high knowledge viewers are less influenced by the quality of the display than low knowledge viewers (Freedman & Shah, 2002; Shah, 2001; Shah et al., forthcoming). These results, which are likely to hold for other kinds of visualizations, suggest that the design of visualizations for typically low-knowledge students needs to be done with more care than for expert users.

CONCLUSIONS

In summary, this brief review of the use of visual displays in e-learning suggests that diagrams, graphs, videos, and other visualizations can help students grasp the relevant information and increase memory for that information. However, limitations in cognitive resources combined with the extensive cognitive demands of comprehending visualizations serve as a major constraint on the effectiveness of visualizations in e-learning contexts. In this article, we outlined a number of principles that arise from the goal of limiting cognitive demands of visualizations and promoting learning. We argued that these principles might be most important for learners with poor visuospatial abilities and suggest that a goal of designing visualizations might be to benefit those who have difficulty with visualizations rather than those who can easily comprehend them.

A crucial lesson is that designers should focus on fostering the construction of the desired visuospatial representation rather than increasing the technological sophistication of visualizations. As Mayer (in press) states, multimedia learning is filled with "commonsense" beliefs that are contradicted by the empirical literature. Furthermore, there is often too little research to support many claims about the use of external representations in e-learning environments (van Bruggen et al., 2002). A deeper understanding of visuospatial cognition can facilitate learning in electronic environments. As Mayer (2002) advocates, it is our hope that this type of exchange between educational researchers and cognitive psychologists will produce better educational technology.

Although this article has focused on the comprehension of complex visualization, e-learning may involve not just presenting such visual information to students, but also asking them to create graphics, diagrams, and illustrations (van Bruggen et al., 2002). Constructing complex visualizations may motivate students, especially when they share their products with fellow students. Moreover, developing visualizations compel students to consider the key components and relations and they may discover what concepts they comprehend and what they do not (Shah, in press). Finally, communicating with other students may force students to consider other perspectives (van Bruggen et al., 2002). Thus, the creation of visualizations, in addition to passive viewing or interaction

with visualizations, has the ability to promote understanding and memory for computer-based instructions.

REFERENCES

Blades, M., & Spencer, C. (1989). Young children's ability to use coordinate references. *Journal of Genetic Psychology, 150,* 5-18.

Clark, J. M., & Paivio, A. (1991). Dual coding theory and education. *Educational Psychology Review, 3,* 149-210.

Freedman, E. G., & Shah, P. S. (2002). Toward a model of knowledge-based graph comprehension. In M. Hegarty, B. Meyer, & N. Hari Narayanan (Eds.), *Diagrammatic representation and inference* (pp. 8-31). Berlin: Springer-Verlag.

Gyselinck, V., Cornoldi, C., Dubois, V., De Beni, R., & Ehrlich, M.-F. (2002). Visuo-spatial memory and phonological loop in learning from multimedia. *Applied Cognitive Psychology, 16,* 665-685.

Halpern, D. F., & Collaer, M. L. (in press). Sex differences in visuospatial abilities: More than meets the eye. In P. Shah & A. Miyake (Eds.), *Handbook of visuospatial thinking*. New York: Cambridge University Press.

Hegarty, M., & Just, M. A. (1993). Constructing mental models of machines from text and diagrams. *Journal of Memory and Language, 32,* 717-742.

Hegarty M., & Kozhevnikov, M. (1999). Spatial abilities, working memory and mechanical reasoning. In J. Gero & B. Tversky (Eds.) *Visual and spatial reasoning in design.* Sydney, Australia: Key Centre of Design and Cognition.

Hegarty, M., Quilici, J., Narayanan, N. H., Holmquist, S., & Moreno, R. (1999). Designing multimedia manuals that explain howmachines work: Lessons from evaluation of a theory-based design. *Journal of Educational Multimedia and Hypermedia, 8,* 119-150.

Hegarty, M., & Sims, V. K. (1994). Individual differences in mental animation during mechanical reasoning. *Memory & Cognition, 22,* 411-430.

Hegarty, M., & Steinhoff, K. (1997). Individual differences in use of diagrams as external memory in mechanical reasoning, *Learning and Individual Differences, 9,* 19-42.

Kozhevnikov, M., Hegarty, M., & Mayer (2002). Revising the visualizer/verbalizer dimension: Evidence for two types of visualizers. *Cognition and Instruction, 20,* 47-78.

Larkin, J. H., & Simon, H. A. (1987). Why a diagram is (sometimes) worth ten thousand words. *Cognitive Science, 11,* 65-99.

Mayer, R. E. (1993). Illustrations that instruct. In R. Glaser (Ed.), *Advances in instructional psychology* (Vol. 5, pp. 253-284). Hillsdale, NJ: Erlbaum.

Mayer, R. E. (2001). *Multimedia learning.* New York: Cambridge University Press.

Mayer, R. E. (2002). Cognitive theory and the design of multimedia instruction: An example of the two-way street between cognition and instruction. *New Directions for Teaching and Learning, 89,* 55-71.

Mayer, R. E. (in press). Multimedia learning: Guiding visuospatial thinking with instructional animation. In P. Shah & A. Miyake (Eds.), *Handbook of visuospatial thinking.* New York: Cambridge University Press.

Mayer, R. E., Heiser, J., & Lonn, S. (2001). Cognitive constraints on multimedia learning: When presenting more material results in less understanding. *Journal of Educational Psychology, 93,* 187-198.

Michas, I. C., & Berry, D. C. (2001). Learning a procedural task: Effectiveness of multimedia presentations. *Applied Cognitive Psychology, 14,* 555-575.

Miyake, A., & Shah, P. (Eds.) (1999). *Models of working memory: Mechanisms of active maintenance and executive control.* New York: Cambridge University Press.

Narayanan, N. H., & Hegarty, M. (1998). On designing comprehensible interactive hypermedia manuals. *International Journal of Human-Computer Studies, 48,* 267-301.

Oestermeier, U., & Hesse, F. W. (2000). Verbal and visual causal arguments. *Cognition, 75,* 65-104.

Pane, J. F., Corbett, A. T., & John, B. E. (1996). Assessing dynamics in computer-based instruction. In M. J. Tauber (Ed.), *Proceedings of the ACM conference on human factors in computing systems* (pp. 797-804), Vancouver: ACM.

Park, O., & Gittelman, S. S. (1992). Selective use of animation and feedback in computer-based instruction. *Educational Technology, Research, and Development, 40,* 27-38.

Rieber, L. P. (1990). Using computer animated graphics with science instruction with children. *Journal of Educational Psychology; 82,* 135-140.

Robinson, D. H., & Skinner, C. H. (1996). Why graphic organizers facilitate search processes: Fewer words or computionally efficient indexing? *Contemporary Educational Psychology, 21,* 166-180.

Schwartz, D. L., & Black, J. B. (1996). Analog imagery in mental model reasoning: Depictive models. *Cognitive Psychology, 30,* 154-219.

Shah, P. (2001). Graph comprehension: The role of format, content, and individual differences. In M. Anderson, B. Mayer, & P. Olivier (Eds.), *Diagrammatic representation and reasoning* (pp. 173-185). Berlin: Springer-Verlag.

Shah, P. (in press). Memory for graphics, diagrams, and videos. In *Encyclopedia of education.* New York: Macmillan.

Shah, P., Freedman, E. G., & Vekiri, I. (in press). The presentation and comprehension of graphically-presented data. In P. Shah & A. Miyake (Eds.), *Handbook of visuospatial thinking.* New York: Cambridge University Press.

Shah, P., & Hoeffner, J. (2002). Review of graph comprehension research: Implications for instruction. *Educational Psychology Review, 14,* 47-69.

Shah, P., Mayer, R. E., & Hegarty, M. (1999). Graphs as aids to knowledge construction: Signaling techniques for guiding the process of graph comprehension. *Journal of Educational Psychology, 91,* 690-702.

Somerville, S. C., & Bryant, P. E. (1985). Young children's use of spatial coordinates. *Child Development, 56,* 604-613.

Subrahmanyam, K., & Greenfield, P. M. (1994). Effect of video game practice on spatial skills in girls and boys. *Journal of Applied Developmental Psychology, 15,* 13-32.

Sweller, J., van Merrienboer, J. J. G., & Paas, F. G. W. C. (1998). Cognitive architecture and instructional design. *Educational Psychology Review, 10,* 251-296.

Tversky, B., Morrison, J. B., & Betrancourt, M. (2002). Animation: Can it facilitate? *International Journal of Human-Computer Studies, 57,* 247-262.

van Bruggen, J. M., Kirschner, P. A., & Jochems, W. (2002). External representation of argumentation in CSCL and the management of cognitive load. *Learning and Instruction, 12,* 121–138.

VanderStoep, S. W., Fagerlin, A., & Feenstra, J. S. (2000). What do students remember from introductory psychology? *Teaching of Psychology, 27,* 89-92.

Vekiri, I. (2001). *An investigation of the role of graphical design and student characteristics in scientific reasoning with weather maps.* Unpublished doctoral dissertation, University of Michigan, Ann Arbor.

Wickens, C. D., Vincow, M., & Yeh, M. (in press). Design applications of visual spatial thinking: The importance of frame of reference. In P. Shah & A. Miyake (Eds.), *Handbook of visuospatial thinking.* New York: Cambridge University Press.

Wiley, J., & Voss, J. F. (1999). Constructing originals from multiple sources: Tasks that promote understanding and not just memory for texts. *Journal of Educational Psychology, 91,* 301-311.

Winn, B. (1987). Charts, graphs, and diagrams in educational materials. In D. Willows & H. A. Houghton (Eds.), *The psychology of illustration.* New York: Springer-Verlag.

Zhang, J. (1997). The nature of external representations in problem solving. *Cognitive Science, 21,* 179–217.

Zhang, J., & Norman, D. A. (1994). Representations in distributed cognitive tasks. *Cognitive Science, 18,* 87–122.

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